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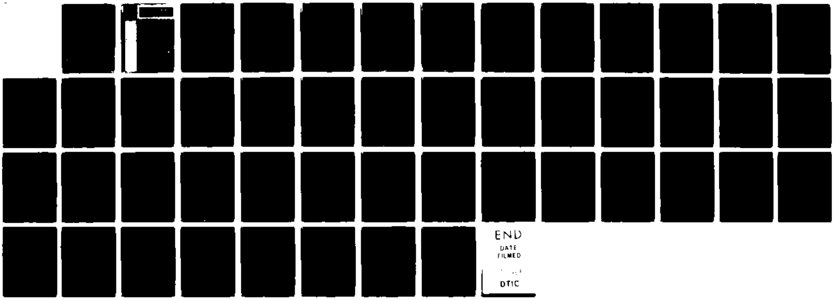

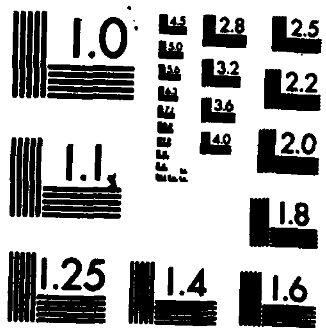

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CINDAS REPORT 32

AD A128905

PROPERTIES OF GRAPHITE INTERCALATES AND OF AIRCRAFT STRUCTURAL METALS AND ALLOYS

A Comprehensive Data Survey

Y. S. TOULOUKIAN
Director

C. Y. HO
Assistant Director - Research

Prepared for

LASER HARDENED MATERIALS AND STRUCTURES SUBPANEL
High Energy Laser Review Group

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents the results of a comprehensive literature search and data survey for the electrical, electronic, optical, and thermal radiative properties of graphite intercalates and for the thermal conductivity, thermal diffusivity, thermal expansion, specific heat, and heat of fusion of several aircraft structural metals and alloys for both the solid and liquid states in the vicinity of the melting point.

The findings on the properties of graphite intercalates are summarized in

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20. ABSTRACT (Cont)

the table on the next page, where the letter "D" indicates the availability of some data for that property of that material.

PROPERTIES OF GRAPHITE INTERCALATES AND OF AIRCRAFT STRUCTURAL METALS AND ALLOYS

A Comprehensive Data Survey

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FOREWORD

This comprehensive literature search and data survey was conducted by the Thermophysical and Electronic Properties Information Analysis Center (TEPIAC), a DoD Information Analysis Center operated by the Thermophysical Properties Research Center (TPRC), Purdue University, West Lafayette, Indiana.

The survey was to provide the urgently needed information to the Laser Hardened Materials and Structures Subpanel of the High Energy Laser Review Group (HELRG).

SUMMARY

This report presents the results of a comprehensive literature search and data survey for the electrical, electronic, optical, and thermal radiative properties of graphite intercalates and for the thermal conductivity, thermal diffusivity, thermal expansion, specific heat, and heat of fusion of several aircraft structural metals and alloys for both the solid and liquid states in the vicinity of the melting point.

The findings on the properties of graphite intercalates are summarized in the table on the next page, where the letter "D" indicates the availability of some data for that property of that material.

	Electrical Resistivity	Hall Coefficient	Magnetoresistance	Thermoelectric Power	Energy Gap	Thermionic Emission	Work Function	Emittance	Reflectance
Cesium Carbide (CsC_8)	D		D						
Potassium Carbide (KC_8)	D		D						
Potassium Carbide (KC_{36})	D		D						
Rubidium Carbide (RbC_8)	D		D						
Graphite, Boron Filled				D					
Graphite, Bromide Filled	D	D	D						
Graphite, Bromine Filled				D					
Graphite, Chloride Filled		D							
Graphite, Chlorine Filled	D			D					
Graphite, Fluorine Filled	D								
Graphite, Lithium Acetate Aqueous Solution Filled							D		
Graphite, Nickel Filled	D	D			D				
Graphite, (Nonspecific) Filled	D								
Graphite, Potassium Filled	D			D					
Graphite, Thorium Oxide Filled						D			
Graphite, Thorium Oxide + Nitric Acid Solution Filled							D		
Graphite, Uranium Carbide Filled	D								
Graphite, Yttrium Oxide Filled						D			
Graphite, Yttrium Oxide + Nitric Acid Solution Filled							D		
Graphite, Zirconium Carbide Filled									D
Graphite, Silicon Carbide Bonded								D	D
Graphite, Silicon Carbide Coated								D	

The findings on the thermophysical properties of the several metals and alloys are summarized in the following table with the letters "D" and "V" having the following designations:

D - Data or recommended values available.

V - Data not available but estimated values obtainable.

	Thermal Conductivity		Thermal Diffusivity		Thermal Expansion		Specific Heat		Heat of Fusion
	Immediately		Immediately		Immediately		Immediately		
	Below M.P.	Above M.P.	Below M.P.	Above M.P.	Below M.P.	Above M.P.	Below M.P.	Above M.P.	
Aluminum	D	D	D	D	D	V	D	D	D
Al Alloy 7075-T6	V	V	V	V	V	V	V	V	V
Titanium	D	V	D	V	V	V	D	D	D
Ti Alloy 6Al-4V	V	V	V	V	V	V	V	V	V
Mg + Al Alloys	V	V	V	V	V	V	V	V	D
Stainless Steels AISI 304 and 347	D	V	V	V	V	V	V	V	V

CONTENTS

I. PROPERTIES OF GRAPHITE INTERCALATES

1. INTRODUCTION

Presented in this section are the results of a comprehensive survey of the available data on the electrical, electronic, optical, and thermal radiative properties of graphite intercalates. The properties on which data are uncovered include electrical resistivity, Hall coefficient, magnetoresistance, thermoelectric power, energy gap, thermionic emission, work function, emittance, and reflectance. The materials reported herein include graphite intercalation compounds (which are graphite compounds where atoms and molecules have been inserted into the graphite matrix material thus giving rise to periodically alternating atomic arrangements of the graphite matrix and the introduced material) and graphite-base materials filled with various substances.

The temperature ranges of the available data for the properties of the materials together with the source references are presented in the next subsection. A summary of the findings is given in the SUMMARY.

2. AVAILABLE DATA

A. Electrical Resistivity

Material	Temperature (K)	Reference	Remarks
(1) Cesium Carbide (CsC_8)	50-310	1	
(2) Potassium Carbide (KC_8)	50-300	1	
(3) Potassium Carbide (KC_{36})	50-300	1	
(4) Rubidium Carbide (RbC_8)	50-300	1	
(5a) Graphite, Bromide Filled	93-298	2	Resistance ratio
(5b) Graphite, Bromide Filled	77-2238	3	Resistance ratio
(5c) Graphite, Bromide Filled	90-288	4	Conductance
(6) Graphite, Chlorine Filled	298	3	Resistance ratio
(7) Graphite, Fluorine Filled	90-288	4	Resistance ratio
(8) Graphite, Potassium Filled	90-288	4	
(9) Graphite, Nickel Filled	223-1473	5	
(10) Graphite, (Nonspecific) Filled	203-973	6	
(11) Graphite, Uranium Carbide Filled	253-1173	7	

B. Hall Coefficient

Material	Temperature (K)	Reference	Remarks
(1) Graphite, Bromide Filled	77-2238	3	
(2) Graphite, Chloride Filled	298	3	
(3) Graphite, Nickel Filled	223-1473	6	

C. Magnetoresistance

Material	Temperature (K)	Reference	Remarks
(1) Cesium Carbide (CsC_8)	50-300	1	Magnetic field 4880 G
(2) Potassium Carbide (KC_8)	50-300	1	Magnetic field 4880 G
(3) Potassium Carbide (KC_{36})	50-300	1	Magnetic field 4880 G
(4) Rubidium Carbide (RbC_8)	50-300	1	
(5) Graphite, Bromide Filled	298	3	Magnetic field 0-14000 G

D. Thermoelectric Power

Material	Temperature (K)	Reference	Remarks
(1) Graphite, Boron Filled	298	8	Thermoelectric power
(2) Graphite, Bromine Filled	298	4	Thermoelectric voltage
(3) Graphite, Fluorine Filled	298	4	Thermoelectric voltage
(4) Graphite, Potassium Filled	298	4	Thermoelectric voltage

E. Energy Gap

Material	Temperature (K)	Reference	Remarks
(1) Graphite, Nickel Filled	223-1473	5	

F. Thermionic Emission

Material	Temperature (K)	Reference	Remarks
(1) Graphite, Yttrium Oxide Filled	398-523	9	
(2) Graphite, Thorium Oxide Filled	298-523	9	

G. Work Function

Material	Temperature (K)	Reference	Remarks
(1) Graphite, Lithium Acetate Aqueous Soln Filled	1823	9	
(2) Graphite, Yttrium Oxide + Nitric Acid Soln Filled	1823	9	
(3) Graphite, Thorium Oxide + Nitric Acid Soln Filled	1823	9	

H. Emittance

Material	Temperature (K)	Reference	Remarks
(1a) Graphite, SiC Bonded	505-1617	10	Total normal
(1b) Graphite, SiC Bonded	645-1645	11	Black body radiation
(1c) Graphite, SiC Bonded	645-1645	12	Black body radiation
(2a) Graphite, SiC Coated	645-1645	12	Black body radiation
(2b) Graphite, SiC Coated	645-1645	12	Black body radiation

I. Reflectance

Material	Temperature (K)	Reference	Remarks
(1a) Graphite, SiC Bonded	700-1645	13	Total normal
(1b) Graphite, SiC Bonded	700-1645	14	Total normal
(2) Graphite, ZrC Filled	298	15	Measured data 0-60 Vol.% Graphite

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Ref. No.	TPRC/EPIC No.	
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II. PROPERTIES OF AIRCRAFT STRUCTURAL METALS AND ALLOYS IN THE VICINITY OF THE MELTING POINT

1. INTRODUCTION

Presented in this section are the results of a comprehensive survey of the available data on the thermal conductivity, thermal diffusivity, thermal expansion, specific heat, and heat of fusion of several aircraft structural metals and alloys (aluminum, aluminum alloy 7075-T6, titanium, titanium alloy 6Al-4V, magnesium + aluminum alloys, and stainless steels 304 and 347) for both the solid and liquid states in the vicinity of the melting point. As seen from what is presented in the next subsection, data are not available for most of the cases. However, for each of such cases, the feasibility of estimating the needed values was studied and the possible method for the estimation is discussed.

The temperature ranges of the available data for the properties of the materials together with the source references are presented in the next subsection. A summary of the findings is given in the SUMMARY.

2. AVAILABLE DATA

A. Thermal Conductivity

a. Aluminum

The melting point of pure aluminum is 933.5 K. There are plenty of experimental data on the thermal conductivity and electrical resistivity of pure aluminum near the melting point in solid and liquid states. TPRC has already generated the recommended thermal conductivity values for pure aluminum in solid and liquid states [24].

The temperature ranges of the available thermal conductivity data together with the source references are given in the following table.

Thermal Conductivity of Aluminum

Temperature Range (K)	Reference	Remarks
0-8500	24	Recommended reference values; solid and liquid states.
389-1073	28	Solid and liquid states.
298-1173	3	Solid and liquid states.
273-1073	25a	Solid and liquid states.
973-1273	41	Solid and liquid states.
933-1873	39	Liquid state.
933-8650	21	Liquid state; calculated from electrical resistivity according to the Wiedemann-Franz-Lorenz Law.

b. Aluminum Alloy 7075-T6

The melting range of aluminum alloy 7075-T6 is from 750 to 911 K. This alloy is also designated as 75S-T6. Experimental data on the thermal conductivity of alum-imum alloy 7075-T6 are available up to 700 K and can be extrapolated to the melting point without large uncertainty.

No information is available for the molten alloy. However, since this alloy contains about 90% aluminum, the ratio of the thermal conductivities of the solid and of the liquid aluminum at the melting point, k_s/k_l, may be used as a guide for the rough estimation of the thermal conductivity of this alloy in the molten state.

The temperature ranges of the available thermal conductivity data together with the source references are given in the following table.

Thermal Conductivity of Aluminum Alloy 7075-T6

Temperature Range (K)	Reference	Remarks
117-702	33	75S-T6.
311-700	54	Not original.
117-700	32	Density, thermal expansion coefficient, specific heat, and thermal diffusivity also reported.
117-622	1	
273-573	26	75S-T6.

c. Titanium

The melting point of pure titanium is 1953 K. There are plenty of thermal conductivity data from room temperature to about 1700 K. TPRC has generated the recommended thermal conductivity values covering the range 0 to 1950 K [24].

No information is available for the thermal conductivity of molten titanium. However, since there are electrical resistivity data for pure titanium up to the melting point and above, thermal conductivity of titanium can possibly be estimated for the molten state. The temperature ranges of the available thermal conductivity and electrical resistivity data together with the source references are given in the following two tables.

Thermal Conductivity of Titanium

Temperature Range (K)	Reference	Remarks
0-1950	24	Recommended values.
1006-1499	53, 52	Calculated from thermal diffusivity using different values of specific heat.
1106-1497	19, 49	Electrical resistivity and Lorenz number also reported up to 1500 K.
753-1606	43	Calculated from thermal diffusivity.
900-1700	53	Calculated from thermal diffusivity.
300-1400	34	Measured for bulk and porous specimens; thermal expansion coefficient and electrical resistivity also reported.
1000-1700	2	Thermal diffusivity, heat capacity, and electrical resistivity also reported; data from other references presented.
1000-1700	15	Heat capacity and electrical resistivity also reported up to 1700 K; written in Russian; seems to be original.
1000-1500	53	Calculated from thermal diffusivity using different value of specific heat.
1100-1500	19	Effect of phase transformation from c.p.h. to b.c.c. in titanium studied.

Electrical Resistivity of Titanium

Temperature Range (K)	Reference	Remarks
273-1473	17	Data compiled from other references.
1100-1500	19	Effect of phase transformation from c.p.h. to b.c.c. in titanium studied.
273-2000	9	Electrical resistivity of 3d-transition metals on melting measured; ratio of electrical resistivities above the melting point and below melting point reported; theoretical value of the ratio reported from reference [1] of this paper.
1000-1750	51	
1200-1900	29	99.86 Ti.
300-1400	38	Resistivity and total emissivity of commercial titanium measured.
332-1935	20	Compiled data [see their Reference 53].

d. Titanium Alloy 6Al-4V

The melting range of titanium alloy 6Al-4V is from 1877 to 1933 K. This alloy has the following various designations [50]:

Republic Steel Co., Titanium Metal Division: Ti-6Al-4V
Special Metal Division: RS-120A

Crucible Steel Co., Titanium Division: C-120AV

Harvey Aluminum Co., Titanium Division: HA-6510

Reactive Metal Products: MST-6Al-4V

Aeronautical Material Specifications: 4928A

Military designation: OS-10737

Both thermal conductivity and electrical resistivity data for this alloy have been reported up to about 1200 K. However, most of the data are from company literature and, therefore, they are only nominal values. There is no data available at all above 1200 K at the present time.

One way to obtain estimates of the thermal conductivity values of the solid near the melting point is to extrapolate the thermal conductivity curve to the melting point following the thermal conductivity curve of pure titanium. The extrapolation can be done reasonably well by adjusting the thermal conductivity values to be consistent with the electrical resistivity values extrapolated in a similar way. At 1089 K the thermal conductivity of this alloy differs only by about 25% from that of pure titanium. The difference between them might decrease further at higher temperatures. Therefore, the extrapolated thermal conductivity values near the melting point will be fairly reasonable and the uncertainties will be within about 10%.

No information is available for the thermal conductivity of this alloy in the molten state. Rough estimates might be obtained by assuming that k_s/k_ℓ of this alloy at the melting point is the same as that of pure titanium, which, however, is also a rough estimate.

The temperature ranges of the available thermal conductivity and electrical resistivity of this alloy are given in the following two tables.

Thermal Conductivity of Titanium Alloy 6Al-4V

Temperature Range (K)	Reference	Remarks
311-811	7	Electrical resistivity reported.
422-922	37	
300-1173	23	Literature data reported including those on density and specific heat.
293-1144	6	Nominal values from a company bulletin.
33-1089	8	Compiled data.

Electrical Resistivity of Titanium Alloy 6Al-4V

Temperature Range (K)	Reference	Remarks
311-1256	5	Compiled data.
293-1173	22	$\Delta R/R_0$ reported.

e. Magnesium + Aluminum Alloys

The melting ranges of Mg + Al alloys are from 923 (pure Mg) to above 710 K depending on the composition. The solubility of Al in Mg is about 12.7% Al. Thermal conductivities of Mg + Al alloys have been reported up to 736 K. TPRC has already generated the recommended electrical resistivity values for the solid solution region up to near the melting point and is generating the recommended thermal conductivity values.

Thermal conductivity or electrical resistivity data for molten Mg + Al alloys have not been reported. Rough estimates of the thermal conductivity for the molten state might be made by assuming that the ratio of the electrical resistivities of the solid and of the molten alloy, ρ_s/ρ_ℓ, at the melting point is the same as that of pure magnesium.

The temperature ranges of the available thermal conductivity and electrical resistivity data together with the source references are given in the following two tables.

Thermal Conductivity of Mg + Al Alloys

Temperature Range (K)	Reference	Remarks
373-623	36	11% and 6% Al alloys.
375-736	18	0.8% Al alloy.
387-674	18	Magnox; 8 ~ 9% Al, 0.501% Zn, and 0.2% Mn.
293-773	40	Magnox B; 1.0% Al and 0.002-0.003% Be; data for pure Mg and many other Mg alloys also reported up to 773 K.
87-476	35	6%, 8%, and 12% Al alloys.

Electrical Resistivity of Mg + Al Alloys

Temperature Range (K)	Reference	Remarks
293.2	44	9 specimens with composition ranging from 0.32 to 2.67% Al.
293-773	40	Magnox B; 1.0% Al and 0.002-0.003% Be.
87-476	35	6%, 8%, and 12% Al alloys.

f. Stainless Steels 304 and 347

The melting range of stainless steel 304 is from 1672 to 1728 K and that of stainless steel 347 is from 1672 to 1700 K.

Russian 18-8 stainless steel seems to be the same alloy as the stainless steel 304. Stainless steel 304L is not the same as the stainless steel 304 but the amount of each of its constituents is within 1 or 2% of that of the stainless steel 304. Therefore, the data for stainless steel 304L can possibly be used as a guide to extrapolate the data for stainless steel 304.

Experimental data for the thermal conductivity of stainless steel 304 are available up to 1225 K and those for stainless steel 347 up to 1543 K. TPRC has recommended values for the thermal conductivity of stainless steels 304 and 347 up to the melting point [46].

No experimental data are available for the thermal conductivity of either stainless steel 304 or 347 in the molten state. However, since the ratios of electrical resistivities of the liquid and of the solid, ρ_ℓ/ρ_s, at the melting point of pure elements Fe, Ni, and Cr (theoretical value) are available [9, 55], ρ_ℓ/ρ_s of stainless steel 304 and of 347 can probably be estimated by simple mixing rule. Thus, the electrical resistivity of molten stainless steels 304 and 347 can be roughly estimated, from which the thermal conductivity can be estimated roughly.

The temperature ranges of the available thermal conductivity and electrical resistivity data together with the source references are given in the following tables. No data were uncovered for the electrical resistivity of stainless steel 347 at high temperatures.

Thermal Conductivity of Stainless Steel 304

Temperature Range (K)	Reference	Remarks
923-1082	45	Extrapolated up to 1600 K.
373-998	4	Not original; discussed about TPRC's recommendation of the thermal conductivity of stainless steel 304; extrapolated up to 1623 K.
373-998	10	Original data source of the above reference.
442-1225	30	18-8 stainless steel.
573-1673	11,12	Stainless steel 304L.
404-1264	47	Stainless steel 304L.
300-1200	48	Electrical resistivity also reported.

Electrical Resistivity of Stainless Steel 304

Temperature Range (K)	Reference	Remarks
300-1200	48	
373-973	30	18-8 stainless steel.
299-1651	11	304L.
295-1273	47	304L.

Thermal Conductivity of Stainless Steel 347

Temperature Range (K)	Reference	Remarks
362-1174	33	
330-1543	14,13	
273-1173	25a,25b	

g. References

Ref. No.	TPRC/EPIC No.	
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B. Thermal Diffusivity

a. Aluminum

One set of experimental data [19] in the liquid state is available. The values in Ref. 5 are calculated from the TPRC recommended thermal conductivity and the selected values of specific heat and density. These values agree with those in Ref. 4 at M. P. in solid state and agree well with the general trend of the results of Refs. 1 and 3. In liquid state the values are believed to be good within ± 10% of the true values. Schriempf's liquid phase data [19] show a trend of negative temperature dependence which is probably due to the thermocouple response error. The values in Ref. 5 had been revised and extended to higher temperatures to become TPRC's recommended values covering up to 8000 K.

The temperature ranges of the available data together with the source references are given in the following table.

Thermal Diffusivity of Aluminum

Temperature Range (K)	Reference	Remarks
365-754	1	General trend of temperature dependence consistent among the three curves.
349-823	1	
340-829	1	
326-799	2	Temperature dependence markedly different from the above set of curves.
295-408	3	Temperature range narrow, supersedes the above 4 curves only barely but temperature range is seen to agree with those of Ref. 1.
933	4	Solid state at M. P.
1-1500	5	Calculated from TPRC recommended thermal conductivity, specific heat, and density.
293-1073	19	In solid and liquid states.
2-8000	20	Recommended values.

b. Aluminum Alloy 7075-T6

No experimental data are available in the liquid state. In solid state, no data are available above 793 K. To obtain values beyond this temperature, three methods are presently applicable:

(1) If the thermal conductivity in the liquid state is known, then the diffusivity can be calculated from the thermal conductivity, the specific heat, and the density. Usually those data are not available, but for specific heat and

density the values can be calculated from that of each of the component element with reasonable reliability, more reliable than in the solid state, by the simple additive formula

$$P_a = \sum_i c_i P_i \qquad (1)$$

where P_i indicates the property of the ith component and c_i is its concentration in the alloy. Even the thermal conductivity values in liquid state may be calculated using a formula similar to the one given by Filippov and Novoselova [8]:

$$k_a = \sum_i c_i k_i - \frac{1}{2} \sum_{i,j} 0.72\, k_i - k_j\, c_i c_j \qquad (2)$$

though the accuracy of the result is questionable.

(2) We may correlate the values of α_s/α_ℓ of the elements at M.P., then generate a simple relation for the alloy and calculate the value in the liquid state from the known solid state value. This method cannot generate values beyond the immediate neighborhood of M.P.

(3) Thermal diffusivity values may be calculated from a formula similar to Eq. (2). Actually, all three methods may be used to complement each other to obtain the best result.

The temperature ranges of the available data together with the source references are given in the following table.

Thermal Diffusivity of Aluminum Alloy 7075-T6

Temperature Range (K)	Reference	Remarks
348.2	6	
373-643	6	
348-793	6	
348,473	6	
348-633	6	
373-603	6	
513,653	6	
473,673	6	
348-583	6	
773,783	6	
116-700	7	Calculated from measured thermal conductivity, specific heat, and density.
144-700	7	Same as above.

c. Titanium

Recommended values are available up to the melting point, but no experimental data or estimated values are available for the liquid state. However, values for the liquid state can be calculated from the thermal conductivity, the specific heat, and the density values.

The temperature ranges of the available data together with the source references are given in the following table.

Thermal Diffusivity of Titanium

Temperature Range (K)	Reference	Remarks
1168-1598	9	
1023-1506	10	Values lower than others.
1056-1662	11	Values relatively high.
885-1596	12	
1000-1700	13	Values high.
1-1953	5	Calculated from TPRC recommended thermal conductivity and selected specific heat and density.
1-1953	20	Recommended values.

d. Titanium Alloy 6Al-4V

In solid state the thermal diffusivity have been measured up to 1183 K, about 740 K below the melting point. No data are available for the liquid state. For extrapolation of data to higher temperatures and for estimation of values for the molten alloy, the same methods as those discussed in the section on aluminum alloy 7075-T6 may be used.

The temperature ranges of the available data together with the source references are given in the following table.

Thermal Diffusivity of Titanium Alloy 6Al-4V

Temperature Range (K)	Reference	Remarks
398-1118	6	
448-1023	6	
373-1183	6	

e. Magnesium + Aluminum Alloys

Experimental data are available up to 623 K for one alloy and up to 589 K for another. For extrapolation and estimation of values in the vicinity of the melting point, the same methods as those discussed in the section on aluminum alloy 7075-T6 may be used.

The temperature ranges of the available data together with the source references are given in the following table.

Thermal Diffusivity of Magnesium + Aluminum Alloys

Temperature Range (K)	Reference	Remarks
116-589	14	94.34/95.94 Mg, 2.5/3.5 Al, 0.7/1.3 Zn, 0.2 Mn, and others.
116-589	14	Same as above.
298-623	15	95.3 Mg, 3.0 Al, 1.0 Zn, 0.2 Mn, and others.

f. Stainless Steels 304 and 347

No data are available in the vicinity of the melting point. For extimation of such values, the same methods as those discussed in the section on aluminum alloy 7075-T6 may be used.

The temperature ranges of the available data together with the source references are given in the following two tables.

Thermal Diffusivity of Stainless Steel 304

Temperature Range (K)	Reference	Remarks
291-1261	16	Data consistent.
403-1243	16	Data consistent.
460-1273	16	Data consistent.
1043	16	Data consistent.
552-1390	17	Having larger temperature dependence and higher values.
580-1379	17	Same as above.

Thermal Diffusivity of Stainless Steel 347

Temperature Range (K)	Reference	Remarks
293-1151	16	Data consistent.
361-1097	16	Data consistent.
490-1136	16	Data consistent.
343-1113	16	Data consistent.
615-1036	18	Data consistent.
117-1255	14	Data consistent.

g. References

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C. Thermal Expansion

a. Aluminum

TPRC Report 16 [1] contains values for the density of aluminum from room temperature to 600 K above the melting point. We also have experimental data on thermal linear expansion within two degrees of the melting point. On the basis of this information, obtaining thermal expansion information on aluminum above and below the melting point seems to be no problem.

The temperature ranges of the available data together with the source references are given in the following table.

Thermal Expansion of Aluminum

Temperature Range (K)	Reference	Remarks
0-1600	1	Data on density.
523-923	2	Experimental data.
293-773	3	Experimental data.
293-773	4	Experimental data
293-873	5	Experimental data.
503-929	6	Experimental data.
293-873	7	Experimental data.
273-923	8	Experimental data.
300-900	9	Experimental data.
82-896	10	Experimental data.
293-927	11	Experimental data.
473-931	12	Experimental data.
600-864	13	Experimental data.
273-923	14	Experimental data.
melting point	15	Percent volume change, experimental data.
melting point	16	Theory and other researchers experimental data.
melting point	17	Percent volume change, α_{solid}, α_{liquid}; summary paper.
293-873	18	Experimental data.
297-811	42	Experimental data.

b. Aluminum Alloy 7075-T6

Most of the needed information is in TPRC report 16 [1]. This report has density values well above and below the melting point. We have experimental data up to 700 K; this can be extrapolated up to the melting point by using the slope of the ρ vs T curve in Ref. 1 around the melting point. Also these values can be compared to values extrapolated from our data using the principle of the corresponding states.

The temperature ranges of the available data together with the source references are given in the following table.

Thermal Expansion of Aluminum Alloy 7075-T6

Temperature Range (K)	Reference	Remarks
0-2400	1	Data on density.
116-699	19	Experimental data.
18-573	20	Experimental data.
293-573	21	Experimental data (2 curves).

c. Titanium

TPRC Report 16 has most of the desired information for the density of titanium above and below the melting point. The other experimental data may be extrapolated to the melting point by using the principle of the corresponding states. Therefore, the thermal expansion of titanium can be obtained above and below the melting point.

The temperature ranges of the available data together with the source references are given in the following table.

Thermal Expansion of Titanium

Temperature Range (K)	Reference	Remarks
0-2400	1	Data on density.
293,1473	22	Experimental data.
330-1273	23	Experimental data.
74-1294	24	Experimental data.
273-1273	25	Experimental data.
311-1100	26	Experimental data.
293-1699	27	Experimental data (2 curves).
294-1180	28	Experimental data.
381-1119	29	Experimental data.

d. Titanium Alloy 6Al-4V

We can probably extrapolate the experimental data to the melting point. These values could then be checked using the density values for titanium alloy A-110AT in Ref. 1 as a guide. The density values of alloy A-110AT could also be used as a first approximation for the thermal expansion of alloy 6Al-4V above the melting point. Also, the mixing rule: $P = \sum_i \rho_i x_i$ could be used to check these values above the melting point. The resulting values for alloy 6Al-4V would have greater uncertainty above the melting point than those predictions for Al, 7075-Tb, and Ti previously mentioned.

The temperature ranges of the available data together with the source references are given in the following table.

Thermal Expansion of Titanium Alloy 6Al-4V

Temperature Range (K)	Reference	Remarks
293-1699	27	Experimental data (2 curves).
4-922	30	Experimental data.
310-922	31	Experimental data (4 curves).
275-1366	42	Experimental data.

e. Magnesium + Aluminum Alloys

The melting ranges of Mg-Al alloys are between about 710 and 293 K depending on composition. The available data can probably be extrapolated to the melting point for any composition between 55-99% Mg. Thermal expansion above the melting point may be calculated from the mixing rule. The melting point for a specific composition will have to be read from a phase diagram which may have unknown uncertainty. As a result, thermal expansion will have more uncertainty above the melting point since the melting point may be uncertain and the accuracy of the mixing rule is unknown in this region.

The temperature ranges of the available data together with the source references are given in the following table.

Thermal Expansion of Magnesium + Aluminum Alloys

Temperature Range (K)	Reference	Composition Mg	Composition Al	Remarks
293-573	32	90-96%	10-4%	Experimental data (9 curves).
293-673	32	90	10	Experimental data (2 curves).
293-573	32	~96	4	Experimental data (2 curves).
293-573	33	94	6	Experimental data.
273-673	34	57-98	43-2	Experimental data (14 curves).
293-673	35	99	1	Experimental data.
83-673	36	~96	3	Experimental data (3 curves).
293-673	37	55-97	45-3	Experimental data (8 curves).

f. Stainless Steels 304 and 347

No experimental data are available near the melting point. Some density information is given in Ref. 1. The estimation of thermal expansion to the melting point may be possible by extrapolating the information from Ref. 1 to the melting point. The mixing rule could possibly be used above the melting point. Again, however, the results from the mixing rule here may be rather uncertain.

Information for stainless steel 347 is slightly better than that for 304 because more high-temperature data for 347 are available. However, the rest of the situation is essentially the same. There is no experimental data above the melting point. The thermal expansion to the melting point may possibly be estimated by extrapolating the information from Ref. 1 to the melting point. The mixing rule could possibly be used above the melting point.

The temperature ranges of the available data together with the source references are given in the following two tables.

Thermal Expansion of Stainless Steel 304

Temperature Range (K)	Reference	Remarks
0-1600	1	Data on density only.
89-811	38	Experimental data.
293-806	39	Experimental data.
297-922	43	Experimental data.

Thermal Expansion of Stainless Steel 347

Temperature Range (K)	Reference	Remarks
116-1144	19	Experimental data.
367-1311	40	Experimental data.
300-1494	41	Experimental data.
83-1273	36	Experimental data.
297-1140	42	Experimental data.
294-1255	44	Experimental data.
0-1600	1	Data on density only.

g. References

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D. Specific Heat

a. Aluminum

Experimental data and recommended values are available below and above the melting point. The temperature ranges of the available evaluated data together with the source references are given below.

Specific Heat of Aluminum

Temperature Range (K)	Reference	Remarks
0.1-3000	4	Good coverage.
0.1-2800	13	Excellent coverage, T_m and ΔH_m well established, C_p of liquid also well established.
0-2800	14	Good coverage.

b. Aluminum Alloy 7075-T6

No experimental data are available in the vicinity of the melting point. However, the data can be extrapolated or estimated to the melting point in the solid state, and estimated values for the liquid state are obtainable from the C_p values of the constituent elements using empirical relations and/or the Kopp-Neumann rule.

The temperature ranges of the available data together with the source references are given in the following table.

Specific Heat of Aluminum Alloy 7075-T6

Temperature Range (K)	Reference	Remarks
273-573	10	Applies theoretical model $c = 3nR/M$; agreement poor.
311-644	11	Compilation.
1-800	4	T_m = 750-911 K; also density for 0-2400 K.

c. Titanium

Sufficient data are available. The temperature ranges of the available data together with the source references are given below.

Specific Heat of Titanium

Temperature Range (K)	Reference	Remarks
1-3000	4	Good coverage.
1-3600	13	Good coverage.
0-4000	14	Good coverage.
1969-2315	15	Also reports ΔH_m.
298-2500	16	Compilation, gives T_m and ΔH_m.
298-3500	17	Same as above.
1400-1850	18	
320-1800	19	
1000-1700	20	
400-1900	21	

d. Titanium Alloy 6Al-4V

No data are available in the vicinity of the melting point. Values may be estimated from the C_p values of the constituent elements using empirical relations and/or the Kopp-Neumann rule.

The temperature ranges of the available data together with the source references are given in the following table.

Specific Heat of Titanium Alloy 6Al-4V

Temperature Range (K)	Reference	Remarks
488-922	5	
273-1144	6	
293-1144	7	$T_m \approx 1803$-1908 K.
293-1144	8	
$T_m = 1866$ K	9	

e. Magnesium + Aluminum Alloys

Complete information for only one alloy is available. Since specific heat data are available for Al and Mg, rough estimation of the values for various magnesium + aluminum alloys can be made using various empirical relations and/or Kopp-Neumann rule.

The temperature range of the available data as well as other information is given below.

Specific Heat of Magnesium + Aluminum Alloys

Temperature Range (K)	Reference	Remarks
280-1080	1	Alloy AZ-80; 8 Al, 0.55 Zn, 0.141 Mn, also gives ΔH_m.

f. Stainless Steels 304 and 347

The available data for the solid can be extrapolated to the melting point.

No data are available for the molten steels. From the C_p values of the constituent elements in the liquid state using empirical relations and/or Kopp-Neumann rule, values for stainless steels 304 and 347 in the liquid range can be estimated.

The temperature ranges of the available data together with the source references are given below.

Specific Heat of Stainless Steel 304

Temperature Range (K)	Reference	Remarks
473-1623	2	
$T_m = 1673$	3	
373-1366	4	

Specific Heat of Stainless Steel 347

Temperature Range (K)	Reference	Remarks
1-1500	4	Reports also density for 0-1600 K.
451-1493	12	

g. References

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E. Heat of Fusion

a. Aluminum

Experimental data and recommended value for the heat of fusion of aluminum are available [1].

b. Aluminum Alloy 7075-T6

No data were uncovered from a limited search of literature. Estimated value may be obtained from values of the constituent elements using empirical relations and/or the Kopp-Neumann rule.

c. Titanium

Experimental data and selected value for the heat of fusion of titanium are available [2-4].

d. Titanium Alloy 6Al-4V

No data were uncovered from a limited search of literature. Estimated value may be obtained from values of the constituent elements using empirical relations and/or the Kopp-Neumann rule.

e. Magnesium + Aluminum Alloys

Experimental data are available for only one alloy [5]. The values for the other alloys may be estimated from values of the constituent elements using empirical relations and/or the Kopp-Neumann rule.

f. Stainless Steels 304 and 347

No data were uncovered from a limited search of literature. Estimated values may be obtained from values of the constituent elements using empirical relations and/or the Kopp-Neumann rule.

g. References

Ref. No.	TPRC No.	
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